Mass shift, width broadening and spectral density of ρ-mesons produced in heavy ion collisions

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Modifications of ρ-mesons formed at the last stage of evolution of hadronic matter produced in heavy ion collisions are studied. It is found that while the mass shift is on the order of a few tens of MeV, the width and spectral density become so broad that ρ may lose its identity as a well defined resonance.

The problem of how the properties of hadrons change in hadronic or nuclear matter in comparison to their free space values has attracted a lot of attention. It is clear on physical grounds that the in-medium mass shift and width broadening of a particle are only due to its interaction with the constituents of the medium, for not too dense media anyway. Thus one can use phenomenological information on this interaction to calculate the mass shift and width broadening[1,2].

For meson a scattering on hadron b in the medium the contribution to the self-energy is:

$$\Pi_{ab}(E,p) = -4\pi \int \frac{d^3k}{(2\pi)^3}\, n_b(\omega)\, \frac{\sqrt{s}}{\omega}\, f_{ab}^{(\mathrm{cm})}(s) \tag{1}$$

where E and p are the energy and momentum of the meson, $\omega^2 = m_b^2 + k^2$, n_b is the occupation number, and f_{ab} is the forward scattering amplitude. The normalization of the amplitude corresponds to the standard form of the optical theorem $\sigma = (4\pi/q_{\mathrm{cm}})\mathrm{Im} f^{(\mathrm{cm})}(s)$. The applicability of eq. (1) is limited to those cases where interference between sequential scatterings is negligible. In the limit that the target particles b move nonrelativistically, $\Pi_{ab} = -4\pi f_{ab}^{(b\,\mathrm{rest\,frame})}\rho_b$, where ρ_b is the spatial density. This corresponds to the mass shift and width broadening[2]

$$\Delta m_a(E) = -2\pi \frac{\rho}{m_a} \mathrm{Re} f_{ab}^{(b\,\mathrm{rest\,frame})}(E)\,, \quad \Delta\Gamma_a(E) = \frac{\rho}{m_a}\, k\sigma_{ab}(E)\,. \tag{2}$$

These relations hold also in the general case provided the amplitudes are averaged over momentum distributions of the constituents. We assumed[3] that ρ-mesons are formed during the last stage of the evolution of hadronic matter created in a heavy ion collision,

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when the matter can be considered as a weakly interacting gas of pions and nucleons. This stage is formed when the *local* temperature is on the order of 100 to 150 MeV and when the *local* baryon density is on the order of the normal nucleon density in a nucleus. The description of nuclear matter as such a gas, of course, cannot be considered as a very good one, so it is clear that our results may be only semiquantitative. The main ingredients of our calculation are on-shell $\rho\pi$ and ρN forward scattering amplitudes and total cross sections. The scattering amplitudes were obtained by saturation of the low energy part with resonances and using a combination of vector meson dominance (VMD) and Regge theory at high energy[3]. Using VMD we are restricted to the case of transversally polarized ρ-mesons. One can argue though, that for unpolarized ρ-mesons our results should be multiplied by a factor ranging from 2/3 to 1[3]. Using experimental information on momentum distributions of pions and nucleons and on the π/N ratio shows that $\Delta m_\rho \sim$ tens of MeV, while the width increases by several hundred MeV at beam energies of a few GeV·A and by twice that amount at about a hundred GeV·A.

We also considered[4] the ρ meson dispersion relation for finite temperature and baryon density for momenta up to a GeV/c or so as this is very interesting for the production of dileptons in high energy heavy ion collisions. The dispersion relation is determined by the poles of the propagator after summing over all target species and including the vacuum contribution to the self-energy. In the narrow width approximation we have

$$\begin{aligned} E_R^2(p) &= p^2 + m_\rho^2 + \mathrm{Re}\Pi_{\rho\pi}(p) + \mathrm{Re}\Pi_{\rho N}(p)\,, \\ \gamma(p) &= -\left[\mathrm{Im}\Pi_\rho^{\mathrm{vac}} + \mathrm{Im}\Pi_{\rho\pi}(p) + \mathrm{Im}\Pi_{\rho N}(p)\right]/E_R(p)\,. \end{aligned} \tag{3}$$

where $E(p) = E_R(p) - i\gamma(p)/2$. We can also define a mass shift,

$$\Delta m_\rho(p) = \sqrt{m_\rho^2 + \mathrm{Re}\Pi_{\rho\pi}(p) + \mathrm{Re}\Pi_{\rho N}(p)} - m_\rho \tag{4}$$

While Δm_ρ in eq.(4) coincides with the one in eq.(1) for small $\mathrm{Re}\Pi/m_\rho$, the two definitions of width correspond to the rest frame of the ρ-meson (eq.(2)) and to that of the thermal system (eq.(3)) and differ by the time dilation factor, $\gamma = \Gamma m_\rho/E_R(p)$.

We evaluate Δm and γ for $T = 100$ and 150 MeV and nucleon densities of 0, 1 and 2 times normal nuclear matter density (0.155 nucleons/fm^3). This is done by utilizing a Fermi-Dirac distribution for nucleons. The nucleon chemical potentials are 745 and 820 MeV for densities of 1 and 2 times normal at $T = 100$ MeV, and 540 and 645 MeV for densities of 1 and 2 times normal at $T = 150$ MeV. Anti-nucleons are not included.

Fig.1 shows the mass shift for different temperatures and nucleon densities (in units of normal nuclear density). The effect with pions alone is negligible (on the order of 1 MeV). The main effect comes from nucleons. The effective mass increases with nucleon density and with momentum, but is almost independent of temperature. These trends and numbers are roughly consistent with other analyses [5].

Fig.2 shows the behavior of the ρ meson width $\gamma(p)$. Once again pions have very little effect. The main effect comes from nucleons. Contrary to ρ mesons moving in vacuum or through a pure pion gas the width remains roughly constant with momentum when nucleons are present. The width is about 240 MeV at 1 times nuclear density and about 370 MeV at 2 times nuclear density. This means that the ρ meson becomes a rather poorly defined excitation with increasing nucleon density.

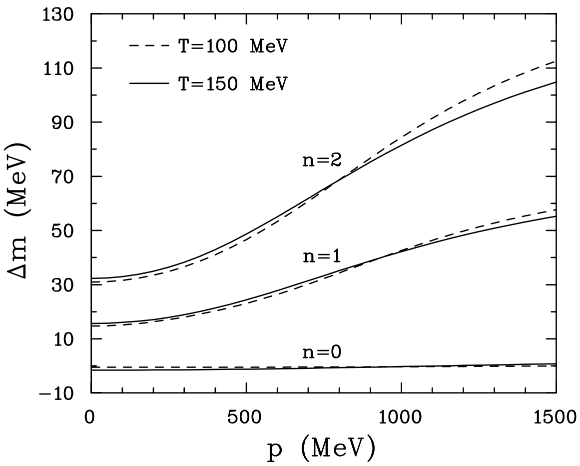

Figure 1. The ρ meson mass shift (eq.(4)) as a function of momentum.

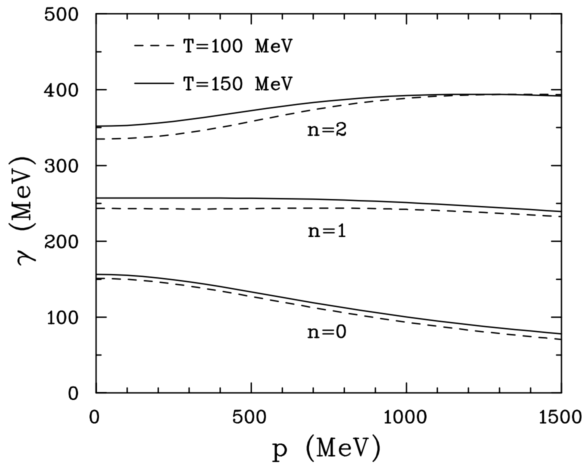

Figure 2. The ρ meson width $\gamma(p)$ (eq.(3)) as a function of momentum.

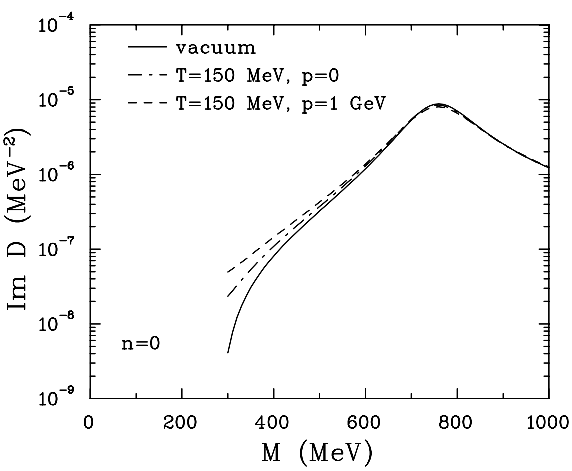

Figure 3. The imaginary part of the ρ propagator. No nucleons.

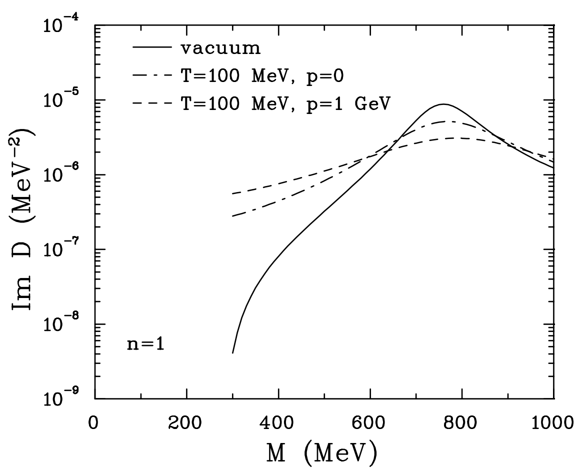

Figure 4. The imaginary part pf the ρ propagator. With nucleons.

The rate of dilepton production is proportional to the imaginary part of the photon self-energy [6] which is itself proportional to the imaginary part of the ρ meson propagator because of VDM[7].

$$E_+E_-\frac{dR}{d^3p_+d^3p_-} \propto \frac{-\mathrm{Im}\Pi_\rho}{[M^2-m_\rho^2-\mathrm{Re}\Pi_\rho]^2+[\mathrm{Im}\Pi_\rho]^2} \tag{5}$$

The vacuum part of Π_ρ can only depend on the invariant mass, $M^2 = E^2 - p^2$, whereas the matter parts can depend on E and p separately. Since we are using the on-shell amplutudes, the matter parts only depend on p because M is fixed at m_ρ. The vacuum parts are obtained from the Gounaris-Sakurai formula [7]. The imaginary part of the propagator is proportional to the spectral density. The former is plotted in Fig.3 for a pure pion gas and in Fig.4 for a gas of pions and nucleons at T and n characteristic of the final stages of a high energy heavy ion collision. Pions have very little effect on the

spectral density even at such a high temperature. The effect of nucleons, however, is dramatic. The spectral density is greatly broadened, so much so that the very idea of a ρ meson may lose its meaning.

The above remarks on the relative importance of pions and nucleons may need to be re-examined when really applying these calculations to heavy ion collisions, where $\pi/N \sim 6$. The pions seem to be overpopulated in phase space, compared to a thermal Bose-Einstein distribution, and this could be modeled either by introducing a chemical potential for pions or simply by multiplication by an overall normalization factor. Pions would need to be enhanced by a substantial factor (5 or more) to make a noticeable contribution at a density of 0.155 nucleons per fm^3[3].

Recently data in Pb-Au collisions at 160 GeV·A have been presented [8] where it was found that the ρ-peak is absent at $k_T(e^+e^-) < 400$ MeV, but reappears at $k_T(e^+e^-) > 400$ MeV. This seems to be just the opposite of our findings. However, our calculations refer to the ρ momentum relative to the *local* rest frame of the matter and a low momentum ρ may actually be moving faster relative to the outflowing matter than a higher momentum one. No conclusion can really be drawn without putting our results into a space-time model of the evolution of matter.

In summary, we have studied the properties of the neutral ρ meson in the gas of pions and nucleons with experimental and thermal momentum distributions. In the former case, pions give the dominant effect, in the latter case they are not important. This difference is due to completely different π/N ratios. However, in both cases interaction with the gas provides a generally positive mass shift for the ρ mesons and greatly increase their width. The ρ meson spectral density is so broadened that the ρ may lose its identity as a well defined particle or resonance. At sufficiently high energy density the matter can no longer be described very well as a gas of noninteracting pions and nucleons. Nevertheless the trends must be obeyed by any realistic calculations of the ρ meson in-medium. Applications to thermal and hydrodynamic models of heavy ion collisions are under investigation.

Acknowledgments

The work reported here was supported in part by the RFBR grant 97-02-16131, CRDF grant RP2-132 and the US Department of Energy grant DE-FG02-87ER40382. V.L.E. thanks the Organizing Committee of QM99 for local support.

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